October 1995 • NREL/TP-411-20018

Photovoltaic Manufacturing Technology Phase 2B: Spheral Solar™ Technology

Final Subcontract Report
24 January 1994 – 23 January 1995

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Dallas, Texas

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
Under Contract No. DE-AC36-83CH10093

NREL/TP-411-20018 • UC Category: 1280 • DE95013144

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Prepared under Subcontract No. ZAI-4-11294-04

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INTRODUCTION

Letter subcontract No. ZAI-4-11294-04 for PVMaT Phase 2B was issued from the National Renewable Energy Laboratory Division of the Midwest Research Institute (NREL) to Texas Instruments Incorporated (TI) on January 24, 1994. This letter subcontract was later definitized on December 8, 1994. The subcontract which is entitled "Photovoltaic Manufacturing Technology - Phase 2B - Spheral Solar™ Technology" was issued with the expectation of improving this technology product quality and accelerating the scale-up of production thus resulting in substantial reductions in manufacturing costs.

This report includes the Annual Report requirements for 1994, as required by the above subcontract.

The Spheral Solar™ technology manufacturing sequence is divided into three major process areas: sphere fabrication, cell build and module assembly. The objective of the first year of this subcontract was to conduct parallel efforts that address significant portions of the Spheral Solar™ PV cell and module manufacturing process. Included in these efforts were to be tasks to: increase the efficiency of the spheres, cells and modules; increase the yield and throughput of spheres and cells; increase the fabricated cell reliability; and reduce cell and module labor costs. Studies were also to be performed on module producibility, module production line flows, increased automation, and required module specifications.

Excellent progress has been made in all of these areas as TI has continued process development on the current pilot line. Critical, higher risk pieces of production scale equipment have been added to the line for early problem identification, redesign and process modification. Other sub-processes have had production scale equipment concepts developed and prototyped. This report will address each of the tasks as stated in the first year objectives. Accomplishments and progress will be highlighted in each task, thus providing a picture of the Spheral Solar™ Technology status toward obtaining the overall PVMaT 2B program goals.

SPHERAL SOLAR™ TECHNOLOGY BACKGROUND

Texas Instruments (TI), with funding from the Department of Energy (PVMaT Phase 2B) and Southern California Edison (SCE), has worked for more than ten years to develop the Spheral Solar™ photovoltaic technology into a commercial product. From the start of this program, TI focused on:

- Developing more cost effective materials than the traditional crystalline silicon cells;
- Sharply increasing yields of spheres and cells from the processed raw material;
- Increasing cell and module efficiencies to industry standards through a variety of material substitutions, material treatments, and bonding procedures;
- Using advanced process controls developed in our Materials and Semiconductor businesses to ensure uniform and low-cost production of large volumes of PV cell and modules;
- Applying our expertise in advanced automation techniques developed for semiconductor and materials production to high-volume PV module fabrication.

The focus of the program has always been to use cost-effective materials in the fabrication and assembly of the PV module. The core of the Spheral Solar™ technology is the use of low-cost silicon (low purity silicon, fines, etc.) and aluminum foil for the cell assembly. The silicon feedstock can be metallurgical grade or any of the variety of reject and off-spec semiconductor grade silicons that are available. This ability to utilize virtually any source of silicon (including fines, which currently are not in use in the industry) is a tremendous advantage, both in achieving a low-cost module and in having a good supply even as the market grows over the next 10-20 years.

Developments carried out with DOE support under a PVMaT Phase 2B contract have set new records in efficiency (10.3% module efficiency) and yield (>80% cell yield). In addition, process repeatability has been demonstrated with sustained operation of the pilot production line, and the scale-up of two of the key processes (sphere melt and cell front bond) has been demonstrated with automated equipment. These accomplishments confirm the potential of this technology to achieve the $2.00/watt cost goal set for the PVMaT2B program.

Since beginning this research effort, TI has applied its more than 50 years of materials processing and silicon fabrication experience to solve a host of difficult engineering and materials problems. It has consistently improved reliability, materials yields, and efficiency as it has scaled up its technology from 1 to 10 to 100 cm^2 cells.

Current Manufacturing Process:

The manufacturing process now in place on the pilot line can be broken down into four main areas:

1. Sphere fabrication
2. Sphere junction formation and finishing
3. Cell fabrication
4. Module assembly.

For each of these areas, a short description of the processes is given below.

1. Sphere Fabrication

This process sequence accomplishes two purposes simultaneously: it purifies the silicon, if necessary, and it forms the spheral shape of the proper diameter. The process can use small chunks of silicon as the feedstock, or silicon fines (50-300 microns) can be used and fused into a sphere of the desired mass. Fusing the silicon powder is the best option because the feedstock is lower cost, the utilization of the silicon is maximized, and the finished sphere diameter is much more tightly controlled.

Following the powder fusing step and an oxide removal, one or more melt operations are performed. The number of melt steps is determined by the purity of the silicon feedstock (i.e., how much purification is required) and the initial roundness of the feedstock. Typically, there are two melt steps required. The processing between melts can also vary depending on the degree of purification necessary; for "dirty" feedstock a mechanical grind is performed to remove the impurities that have been segregated to the surface of the sphere during the melt/freeze operation. For feedstocks such as off-spec semiconductor grade silicon, a simple oxide removal with dilute hydrofluoric acid is sufficient.

The final step in forming the silicon spheres is an acid etch using a mixture of nitric and hydrofluoric acid to provide a high quality surface for forming the junction. Etching with a caustic such as sodium hydroxide is a possible substitute for the nitric:hydrofluoric solution.

2. Sphere Junction Formation and Finishing

After attaining the required purity, the spheres go through a sequence of processes designed to achieve a high-quality p/n^+ junction. This sequence is:

a. Denuding -- creates a denuded region near the surface by forming oxygen precipitates near the center of the sphere. This is done in an oxygen/nitrogen ambient at about 1200° C. for 48 hours.

b. Diffusion -- forms the n^+ layer on the surface of the p-type sphere by diffusion of phosphorus from a gaseous $POCl_3$ source. This is done at over 900° C. for about two hours. (The TI Spheral Solar™ process requires a deep junction to prevent shunting when bonding the sphere to the aluminum foil). An acid clean (hydrofluoric acid) precedes and follows this step to remove oxide from the surface of the spheres.

c. Segregation Anneal - this step uses the phosphorus diffused layer to getter impurities toward the sphere surface, moving them away from the p/n^+ junction.

3. Cell Fabrication

The cell fabrication process is a combination of mechanical and chemical processes. One of the innovative processes is the bonding of spheres to two pieces of aluminum foil. The front foil serves two distinct purposes: it defines the size and shape of the cell and it is the electrical contact to the n^+ layer. The back foil functions solely as the contact to the p-type core of the spheres.

In the current production process, the front foil is punched with 160-200 holes per square centimeter, depending on the size of the spheres to be bonded into the foil. One sphere is then positioned in each hole by a mechanical process, and held in place by a slight vacuum. Positioning and alignment of the spheres are crucial to the subsequent bonding. An automated robotic workcell is now on line and has demonstrated the capability of this process to be scaled up.

The process used to form the metallurgical bond between the sphere and the foil is a combination of elevated temperature and pressure. The key is to create shear at the bond interface to exposed unoxidized surfaces, diffusing silicon into the aluminum. Thus, an intimate, low resistance bond forms.

After the spheres are bonded to the front foil, they are processed through two acid etches. The first exposes p-type core by removing the n^+ layer from the back of the cell. The second etch thins the n^+ layer on the front side of the cell to increase the current generation in sunlight. Both are spray etch processes done in equipment very similar to printed circuit board etch equipment. In the next generation equipment now being designed under a PVMaT2B contract, these two steps will be combined into one.

Following the etch steps, a layer of polyimide (a polymer used in high-temperature applications) is applied to the back of the cell. This acts as an insulator between the front and back foil (bonded later at the final step in the cell fabrication process). After curing the polyimide in a belt furnace, the cell is mechanically abraded, removing the

polyimide (forming a via or small area of polyimide removal) from the back tips of the spheres. This exposes only the surface of the sphere tips (p-type material) for bonding to the back foil.

In this device structure, all the spheres in the cell (about 18,000 in a 100 cm^2 cell) are in parallel. The entire cell will be shorted if any of the spheres are shorted or shunted. Today there are a small amount of shunted spheres in the cells due to the few residual impurities in the spheres or damage during bonding; this level is unacceptable for mass production. A critical innovation by TI was the selective electro-dissolution (SED) process that electrically isolates the shunted/shorted spheres from the cell. Similar to an anodizing process, in the SED process an oxide is grown on the back surface of the shunted spheres. This is accomplished by applying a reverse voltage to the spheres while immersed in an electrolyte. This oxide insulates the defective spheres from the back foil, thus effectively removing them from the circuit. This innovation is key to the successful use of low-cost silicon feedstocks in large-area solar cells.

Following the SED process a titanium dioxide (TiO_2) coating is deposited on the front surface. This coating serves primarily as an anti-reflective coating to improve the current generation of the finished cell. It also helps to protect the front surface of the spheres during the bonding of the back foil.

The final step in the cell process sequence is back bond. At this step a thin aluminum foil is bonded to the back side of the cell for electrical contact to the p-type sphere core. This is a thermocompression bonding process very similar to front bond.

4. Module Assembly

The module assembly process is unique for crystalline silicon devices in that it requires no additional materials to interconnect the cell. Only silicon and aluminum are present in the laminate, thus reducing potential failure modes. The cell front and back foils provide for interconnections by ultrasonically welding them together. For example, if the cells are connected in series, TI welds the front foil of one cell to the back foil of the adjacent cell. The current carrying ability of the foil (front and back) is adequate for all foreseeable module configurations. Aluminum straps carry current out of the laminate. This technique eliminates the need for interconnecting straps and solder, both of which add assembly complexity and potential reliability problems.

The laminate materials used in the TI Spheral Solar™ module fabrication are Tedlar/polyester/Tedlar laminate backskin, EVA encapsulant, and a tempered glass front cover. The Spheral Solar™ cells have the excellent future potential for flexible packaging, and we are currently working on several options under the PVMaT2B contract.

TASK 1 INCREASE IN SPHERAL MATERIAL YIELD

Task 1 efforts concentrated mainly on the development of tooling and related bonding materials necessary to optimize the use of sphere output. Tooling was identified to utilize as many of the sphere sizes as possible. Likewise communication with the sphere processes allowed the centering of output around the best yielding tools while still maximizing material yields.

Stabilization of the existing processes established in late 1993 was fundamental to reducing variability in the data collected for the PVMaT effort. This included every process from the first sphere processes all the way to cell test. Without stabilization and sizable quantities of repeatable data, locating areas that needed improvement would be difficult. After 3 months of pilot line production, clear trends began to appear in the bonding tooling. The tooling was separated by sphere size, clamshell shims, roll gap settings, and embossed front foil. Table 1 below shows the sphere size for each size of front foil being utilized during this time period. The foil spacing discussed refers to a 60 degree close-packed hexagonal pattern (i.e. the .027 tool refers to a .027" center-to-center spacing between holes in the front foil). The larger the sphere size, the larger the spacing necessary to accommodate the spheres. Based on previous testing, the sphere sizes had to be separated into two size ranges (bins) to enhance the bonding characteristics.

FOIL SPACING	BIN 1 SPHERE RANGES	BIN 2 SPHERE RANGES
.027"	.0246 - .0251"	.0252 - .0258"
.0285"	.0259 - .0265"	.0266 - .0273"
.030"	.0274 - .0280"	.0281 - .0288"
.032"	.0289 - .0298	.0299 - .0308"
.0335"	.0309 - .0315"	.0316 - .0323"

Table 1: Embossed foil spacing and accompanying sphere ranges.

The front bonding parameters were documented next to achieve consistent lot-to-lot processing. Table 2 below shows the parametric settings established. The roll mill used at front bond is a 1948 vintage. Though well maintained, the roll gap settings had to be modified from time to time to maintain consistent bonding pressures. The goal was to maintain approximately 12,000 - 15,000 lbs per side on the roll mill. Past experimentation has shown that this pressure resulted in satisfactory metallurgical bonds between the silicon spheres and aluminum front foil while minimizing damage to the silicon surface.

BASELINE FRONT BOND ROLL MILL & CLAMSHELL SETTINGS			
TOOL SPACING (inches)	LEFT GAP SETTING	RIGHT GAP SETTING	CLAMSHELL SHIMS (side/end)
.027	19.1	22.0	.045/.059
.0285	19.3	22.1	.045/.059
.030	19.1	22.0	.048/.062
.032	19.4	21.5	.048/.062
.0335	19.0	22.0	.351/.065

Table 2: Front bond roll mill gap and clamshell settings.

The above charts show that sphere ranges from .0246" to .0323" were being utilized at this time. This wide range of foil sizes allowed utilization of 90% of the spheres being delivered from the sphere area. Sphere lot sizes were also modified to 400 grams to allow better utilization. Each 12 strip (3 solar cells each) lot utilizes 350-380 grams of sphere material, depending on the foil size. At least 20 grams extra is needed to facilitate flooding of the vacuum chuck during foil loading prior to bond.

The trends mentioned earlier started to show several interesting factors. The trending studies utilized electrical characteristics on finished cells. The electrical tests were already in use and sophisticated enough to dissect the trends. The .032" embossed foil size emerged as both the yield and performance leader. Over time it consistently outperformed the other tools. A measurement study was undertaken to understand differences in the embossed tools being used. A specialty gauge manufacturer was engaged to measure the tools.

Several interesting facts were uncovered: 1) The .032 EDM electrode was subcontracted to another facility rather than made in-house at the machine shop. The tolerances were more consistent and the diameter of the embossing posts as well as the height of the posts was different from the print tolerances. 2) The first tools made by the machine shop showed the most variation in all dimensions. The .030" tool was the first tool they made and this was the worst performer electrically of all the tools. 3) The newer embossing tools were consistent in location in both the X and Y dimensions, however variation was evident in the height of the post (Z dimension) and in diameter consistency. Measurements had been taken when the tooling was received, however our measurement equipment was not sophisticated enough to capture large quantities of data. The measurement equipment that was utilized could measure the entire surface in all directions in a single pass. This provided a better understanding of the entire surface topography.

The resulting actions included rescaling all our tooling to match the dimensions, spacing, and tolerances seen in the best performing .032" tool. New prints were generated and new tools were ordered after we met with the machine shop personnel to explain our findings. New tools were scheduled to arrive in the second half of 1994.

The next major goal for the first six months of 1994 was to secure a new source of front foil aluminum that was more cost effective. The manufacturer that was being used at the time was located in England and the cost per lb was approximately $200. The cost goals for the factory were approximately $6.00 per lb. A U.S. manufacturer was located that was capable of producing the small quantities we needed. The cost negotiated was to roughly $3.00 per lb, excluding manufacturing losses due to melting, rolling and slitting to final size.

Two members of the solar group traveled to this facility to make an experimental run. The run hardened during the billet pouring stage and the yield was very poor. However we did have a chance to experiment with the different anneal and sheet roll down phases. The next step was to order a full melt (approximately 35,000 lbs) and to use the experience gained on the test melt to mimic the grain structure of the more expensive material. This order was received and tested during the second half of 1994.

Stabilization of all cell processes allowed important trending analysis to take place. To maximize the material yield, we first had to understand the best tooling and foil combinations. This information could then be passed to the sphere team. They, in turn, could modify their sphere processes and sieve sizes to center the output around the best performing tools. New understanding of our tooling and material processes also allowed for improvements to be laid in place for the second half of 1994. With factory equipment to starting up in October of 1994, it was imperative to fine tune our processes for production. Several more major changes were still needed to move this program from a limited production line to a factory capable of large quantity outputs.

The second half of 1994 focused in three major areas. First was the changeover from metallurgical grade silicon to semiconductor grade silicon. This posed several new challenges for the front foil bonding area in that the resistivity levels had to be adjusted for the new feedstock. Stabilization of the resistivity and its effect on bonding parameters took several weeks to understand. Generally speaking the higher the resistivity, the more difficult it is to induce a metallurgical bond between the silicon and aluminum front foil. Secondly, as mentioned above, the embossing of front foils did not lend itself to scaling up in a factory environment. Therefore, we also decided to stop embossing the foil and start using punched foil. Punched foil is made with a precision die set as a continuous coil of material is fed through it. The hole profiles between the two methods vary considerably and this added new complications to the fine tuning of the bonding parameters. The third major change involved switching to a new aluminum material supplier. As mentioned earlier, cost was the main driver for this change. This change was required by our cost model.

robotic controlled front bonding line. This line consisted of an automated vacuum chuck loader, robotic foil and pressure pad manipulation, hydraulic pressure controlled roll mill and an integrated heating system with much tighter clearances and more sensitive heating plates to maintain consistent temperatures. The clamshells had to be redesigned to integrate into this system. This new machine introduced a new set of bonding parameter variables that required time to test and understand the interactions that were most important. Tasks 4, 5 and 6 detail the automated bonding line in greater detail. The overall decision to make these changes was based on sacrificing some performance now in order to gain experience on equipment and processes that simulated factory running. Each of these three major changes and their process impacts are addressed in the following paragraphs.

Semiconductor grade silicon:

Please refer to Task 2 for a detailed explanation of the doping processes necessary to achieve the desired sphere resistivity. Testing was done on the established baseline embossed foils to set the needed resistivity. Fluctuations in resistivity caused some bonding problems, however as the sphere team became more familiar with the doping techniques, the consistency from lot to lot improved.

Stamped front foil:

As mentioned before, the punched hole profile was much different from the embossed hole profile. Essentially the punched hole was just that; a straight-walled hole punched through the material. No material deformation was present with the exception of a very small exit burr generated on the back side of the foil. The embossed hole profile was very unique. Embossing utilizes a tool with a post on one side onto which is laid a piece of front foil. The foil and tool are then sent several times through a roll mill that forces the aluminum to flow over the tool and create the pattern needed. This foil is then carefully lifted off the tool and etched. The result is a tapered pocket approximately 3 times thicker than the original material. In other words, the .002-.0025" thick material was leaving approximately a .006" thick pocket for each sphere to sit in. This is where the major difference is between punched and embossed foil.

Punched foil leaves a straight hole that is only as thick as the parent material. Figures 1a and 1b below depict the basic differences between the two methods and how a sphere would look in place. Notice the difference in the depth of the pocket remaining after embossing. Notice also that the hole shapes differ considerably. One can see that movement during the bonding cycle could be reduced when using the embossed foil.

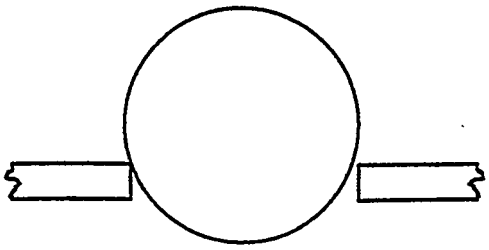

Figure 1a: Punched foil cross section.

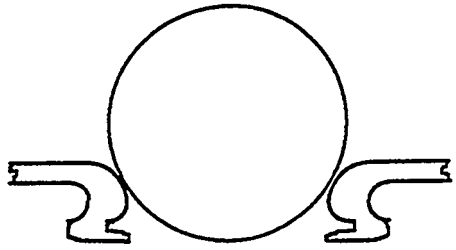

Figure 1b: Embossed foil cross section.

To help reduce the differences between the two methods, a thicker punched foil was chosen for testing. We chose .0035" material for two reasons: 1) It was stiffer than the embossed foil and would lend itself better to automated handling with less damage in a factory environment. 2) It would produce a thicker pocket yet not reduce cell efficiency. However, as depicted in the figures above, too much of the sphere still protrudes past the punched foil surface. The result often is that the spheres do not sit properly on the foil because the vacuum chuck used to load the spheres actually holds the spheres up out of the pocket. Testing to date has shown that movement is still a problem and new .005" foil has been ordered. Studies are also scheduled to experiment with the punched hole sizes.

Front Foil Material Supply:

The new material supplier was set-up to deliver the same alloy as we had used in previous years. The material supplier starts by pouring large 4500 lb ingots utilizing a water cooled jacket to define the shape and length. The ingots are trimmed to remove the oxides and impurities that concentrate in the outer surface. These ingots are then homogenized for 12-15 hours and sent to their plate stock area. An ingot is then rolled down into plate stock from roughly 12" thick material down to .060". The coil of material is then interannealed in an oven for 2 hours and sent to their foil area where the plate is rolled down to the final dimensions, slit and packaged for delivery.

Thermal annealing in our facility is necessary to enhance the grain structure and to stress relieve the material to obtain the flatness needed for front bond. Our goal was to duplicate the material characteristics of the original material as close as possible. The original material was a starting point for the properties. We did not know how much the change from embossed to punched or from one manufacturer to another would influence the overall bonding process. Table 3 below summarizes several months of experimentation and lab analysis performed at the TI Advanced Materials Lab in Attleboro, Massachusetts. A distinction is made between the first test melt and the large second melt due to processing differences at the new manufacturer.

Material Supplier	Condition	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation in 1 inch (%)	Hardness Hv
Original supplier	As received	23.4	30.1	5.4	46.4
	500C 5 min.	2.50	11.8	19.5	21.9
	500C 10 min.	3.25	11.0	19.5	25.4
1st melt new supplier	As received	28.5	33.5	7.8	61
	Heat treated*	5.6	11.7	14.5	25
2nd melt new supplier	As received	21.1	24.5	2.2	48
	Heat treated#	9.2	11.0	3.4	26
	Heat treated~	4.9	8.6	6.8	N/A
	343C 15 min.	5.2	11.1	22.6	N/A

* The thermal treatment was 30 mins. @ 505C followed by 1275 mins @ 333C
# The thermal treatment was 90 mins @ 505C
~ The thermal treatment was 90 mins @ 505C followed by 15 mins @ 343C

Table 3: Property comparison chart between suppliers.

Our goal was to duplicate the original supplier properties at 500 deg C for either the 5 or 10 minute time frame. As one can see, the best match came from a simple anneal (343 deg C 15 min.) from the second melt. Bond adhesion between the silicon and aluminum with the new material was poor prior to anneal and it was believed that this would improve if the elongation properties were matched. Yields with the annealed material are better, however new bonding parameters are still being investigated.

Several important facts have been discovered in the second half of 1994 that could potentially affect material yields. However, until bonding parameters are stabilized and the many process changes mentioned above are incorporated, it will be difficult to predict which areas have the greatest impact on improving material yields.

TASK 2 INCREASE SPHERE THROUGHPUT AND DECREASE LABOR COSTS

The majority of work on Task 2 during the 1994 has been concentrated in developing new equipment and processes for the shape sort, size sort, denude, sphere diagnostics

and fused powder areas. Highlights of the efforts and current status for each of these areas as it pertains to Task 2 are outlined below.

Shape Sorting

Two efforts have been worked in parallel to increase throughput and decrease labor requirements for the Shape Sorting process.

The first involved optimizing the current process which uses an inclined vibratory plate. To do this, tests were completed to characterize how the angle of the incline and amplitude of the vibration affected the quality (roundness) of the sphere sorted, its relation to cell yield during bonding, and the rate at which spheres were sorted. To verify the quality of the spheres a vision system was installed that measures the roundness of samples pulled during testing. This information was then used to set up and monitor a prototype shape sort system that combined 5 vibratory tables into a common piece of equipment. The testing and development of this prototype shape sort system demonstrated a current maximum throughput (approximately 200 grams per hour per table) before the quality of the spheres collected in an acceptable bin degrades. It also helped to identify key equipment design parameters that would allow the combination of multiple inclined vibratory plates into a system to reduce labor requirements.

The second effort was to develop a high throughput shape sort prototype that would result in the design of the factory equipment that could reduce labor and floor space requirements. By studying the current incline vibratory plate, spiral separator and inclined planes, it was observed that certain actions occured that limited throughput or resulted in the mis-classification of spheres (good/bad). By using these observations and the vision system to quantify the sphere quality requirement, a list of requirements was generated for building prototype equipment. The equipment manufacturer took this list and identified five potential concepts that are currently being prototyped. These proof of principle prototypes are scheduled to be tested in February 1995.

Size Sort

As with shape sort, two efforts were pursued in parallel for size sorting to increase throughput and decrease labor requirements.

The first effort involved scaling up and optimizing the existing precision roll sort equipment. This included building a working prototype that demonstrated the feasibility to combine multiple precision roll sorters into one piece of equipment with common sphere feed and collection hoppers to minimize labor requirements. Tests to improve the equipment reliability and sorting accuracy of the prototype have produced new design requirements that will be incorporated in any future roll sort equipment.

Efforts to improve the throughput have not been as successful because the sorting accuracy begins to degrade as throughput increases.

As with shape sort, the parallel effort was to develop a high throughput, low labor proof-of-principle prototype size sorter. To do this the equipment designer developed a slotted rotary disc concept. The initial prototype demonstrated the ability to force spheres into and along a slot at rates up to 15 kg per hour. Based on these results, Battelle incorporated design modifications to address concerns of spheres getting lodged in the slot and to provide flexibility to change the slot configuration during testing. The fabrication of this prototype has been completed and testing is scheduled to complete February 1995.

Denude

A new vertical furnace has been designed and fabricated by MRL Industries for the Denude process to provide higher sphere throughput and to decrease labor costs. A sphere process container that is capable of holding greater than 30 kg of spheres vs. the 1.5 kg for the current containers, has been fabricated and tested. The furnace is designed to process six containers per run giving it a total capacity in excess of 190 kg. Initial inspection and resulting modifications have been completed, and final source inspection and delivery of the furnace are scheduled for January 1995.

Sphere Diagnostics

As part of the effort to increase the lot size of spheres that are processed through each step of production, a method of sphere diagnostics to determine during the early processes if the lot would produce an electrically acceptable product was essential. To address this concern, a Radio Frequency Photo Conductance Decay (RFPCD) system has been constructed based on a design by NREL. Installation of the RFPCD system and initial testing have been completed and produced data showing a correlation between lifetime decay and the quality of finished spheres. Future plans include testing spheres from earlier melts to see if a continued correlation can be established.

Fused Powder Process

Work on the fused powder process included development of both process and factory scale equipment.

Key areas of progress for the process have been: 1) the determination of the furnace power requirements; 2) the definition of the configuration and conveyor speed necessary to completely melt the silicon powder into spheres; 3) the identification of the support material to be used to minimize silicon contamination; 4) the establishment of the starting silicon size range and distribution. As a result of this work, test lots have produced cells with projected module efficiencies of greater than 9%. Current efforts are now directed toward optimizing subsequent processes to improve sphere efficiency.

Work on the equipment has concentrated on designing and building the factory scale furnace based on the process requirements, and on the development of an effective way to dispense the silicon to produce a tight size range (95% within a .006" range) of spheres. The furnace design has been completed, and fabrication and final testing are scheduled to be finished by mid-January 1995. By building and testing various prototype feeders, a perforated rotary drum has been selected as the best method to dispense silicon. Tests structured to replicate the projected perforated rotary drum operating parameters have met the desired size range. A working prototype of the perforated rotary drum has been fabricated and tested. Based on these tests, modifications are being incorporated to improve its performance. Finally, the associated automation to allow continuous production with one to two operators is being designed and is currently being fabricated. The delivery of the perforated rotary drum and Phase I of the automation is projected for February 1995.

TASK 3 INCREASE SPHERE EFFICIENCY

The progress through 1994 on Task 3 has yielded sphere efficiencies of greater than 11% (adjusted for AR coating and encapsulation) thus exceeding the phase III milestone of 10.0%. Modifications to the sphere process flow have resulted in a 50% reduction in the number of process steps required to prepare the silicon for cell fabrication. This reduction directly translates to shorter process cycle time, greater throughput, and lower cost. Other breakthroughs include a new cost effective boron and phosphorus doping processes, and an improved silicon etching process. This section will discuss these as well as other process modifications, feedstock changes and experiments which have been evaluated for potential efficiency gains.

The spheres used in the TI Spheral Solar™ are approximately 0.030" in diameter, making them difficult to measure using conventional means. It is therefore necessary to bond the spheres into aluminum foil to obtain the electrical characteristics. Once the spheres have been bonded, the phosphorous-doped region is removed from the backside of the spheres using a chemical etching process. The cells are then probed under a one-sun solar simulator to determine their open circuit voltage (Voc) and short circuit current (Isc). The efficiencies presented in this report are therefore calculated from spheres mounted in aluminum foil and probed under a one-sun simulator.

The silicon feedstock in use from the beginning of 1994 through April was metallurgical grade (MG) silicon. Because of the high level of impurities in the feedstock, several melt and grind removal steps were required to upgrade the material by lowering the impurities to an acceptable level. The resistivity of this material following the upgrading process was approximately 0.1 ohm-cm. Beginning in May, 1994, the feedstock was changed from MG to off-spec semiconductor grade (SG) silicon. The lower impurity level of the SG material eliminated the need for upgrading but required a doping

process to convert it from high resistivity (>100 ohm-cm) silicon to p-type silicon. Several experiments were conducted to determine the optimal resistivity range for best efficiency, balanced with processing requirements at bond. The best was found to be at about 0.8 ohm-cm.

Surface Passivation and Texturing Treatments:

Several surface passivation techniques were evaluated for increasing efficiency on cells constructed from MG silicon. Because both the front and backside of the spheres are etched after bonding into the aluminum foil, the surface of the silicon must be passivated after bonding. The aluminum foil prevents any conventional high temperature oxidation processes to be performed. Cells coated with silicon nitride after front bond (using a low-temperature plasma-enhanced chemical vapor deposition technique) demonstrated a 20% efficiency boost prior to application of the standard anti-reflective coating. The improvements were however lost once the AR coating was applied. More work needs to be done to better understand this.

Surfaces of the spheres were textured prior to bonding into the foil in an effort to improve sphere efficiency by reduction of reflected light. Several means of chemically texturing the spheres prior to phosphorus deposition were evaluated. Although we were able to demonstrate the ability to successfully texture the spheres, we were unable to demonstrate successful bonding of the textured spheres into the aluminum foil. The work on surface texturing of the spheres is currently on hold pending results from alternate phosphorus dopant tests.

Phosphorus Gettering:

Transmission Electron Microscopy (TEM) results show a significant number of dislocations formed approximately 0.5um below the surface of the silicon following the segregation anneal process. Because these defects are not present immediately following the POCL3 deposition process, they are believed to be caused by phosphorus impurity gettering. Increasing the segregation anneal temperature above 900 degrees C reduces the number of defects but degrades the electrical performance of the spheres. This leads us to believe the higher temperature allows the impurities to redistribute within the active region of the sphere rather than remaining trapped in the inactive outer region. Work on phosphorus gettering optimization is on hold pending results from the alternate phosphorus dopant tests.

Sphere Etch:

Much progress has been made in the silicon sphere etch process. The process is a 19:1 mixture of nitric acid (HNO_3) and 49% hydrofluoric acid (HF). The spheres are etched in the solution to remove surface stress induced during the final melt step, as well as to provide a smooth, shiny surface to facilitate bonding to the aluminum foil. The previous sphere etch process used the chemical heat of reaction to determine the

amount of time the silicon was to remain in the etch bath. This was difficult to control as the bath is much larger than the sphere load and therefore difficult to accurately measure.

The new process controls the temperature of the bath and therefore allows the silicon removal to be controlled by time rather than the heat of reaction. This has allowed us greater control over the amount of silicon removed as well as repeatability from batch to batch. Because of the greater control over the process we can run in a continuous type mode without having to wait for the bath to cool between runs, doubling the throughput of this process.

The demonstration of a continuous flow sphere etching process has allowed us to develop a factory scale equipment concept. A prototype of the factory concept is currently being built to evaluate the ability to etch, rinse, and de-wet the spheres within the same enclosed canister without having to remove or transfer material between processes. The prototype is scheduled to be completed by April of next year with installation and testing scheduled to begin in May of 1995.

Phosphorus Doping:

Much work has been done to better understand and improve the phosphorus doping process. A two-step diffusion process using a low temperature POCL3 deposition followed by a higher temperature drive process resulted in higher cell Voc. The application of a thin (200 angstrom) thermally-grown oxide prior to POCL3 deposition also showed improved cell Voc. These results lead us to believe that our current phosphorus doping process is damaging the surface of the silicon by driving too much phosphorus into it.

Because of the difficulty in uniformly depositing phosphorus over silicon spheres using POCL3, alternate means of doping the spheres have been evaluated. The alternate dopants included liquid "spin-on" types deposited and dried on the surface of the spheres and then driven into the silicon using a high temperature furnace process. Advantages of using a liquid phosphorus dopant source include the ability to uniformly dope the spheres without saturating the surface with phosphorus, increased loadsize from a few hundred grams to several kilograms of material per furnace run, and lower cost. The electrical results from the initial tests show both higher Voc and Isc resulting in cell efficiencies of greater than 11.5%. Work is currently continuing on conversion to this process on the pilot line.

As can be seen in Figures 3 and 4, most of the improvement in the cell efficiency has been realized by the conversion from MG to SG grade silicon. The conversion to SG silicon not only improved the cell efficiency but reduced the number of sphere processes and cycle time by 50%. Pilot line production using the SG silicon has demonstrated an average cell efficiency of 10.5% over a four month period, with many cells over 11%.

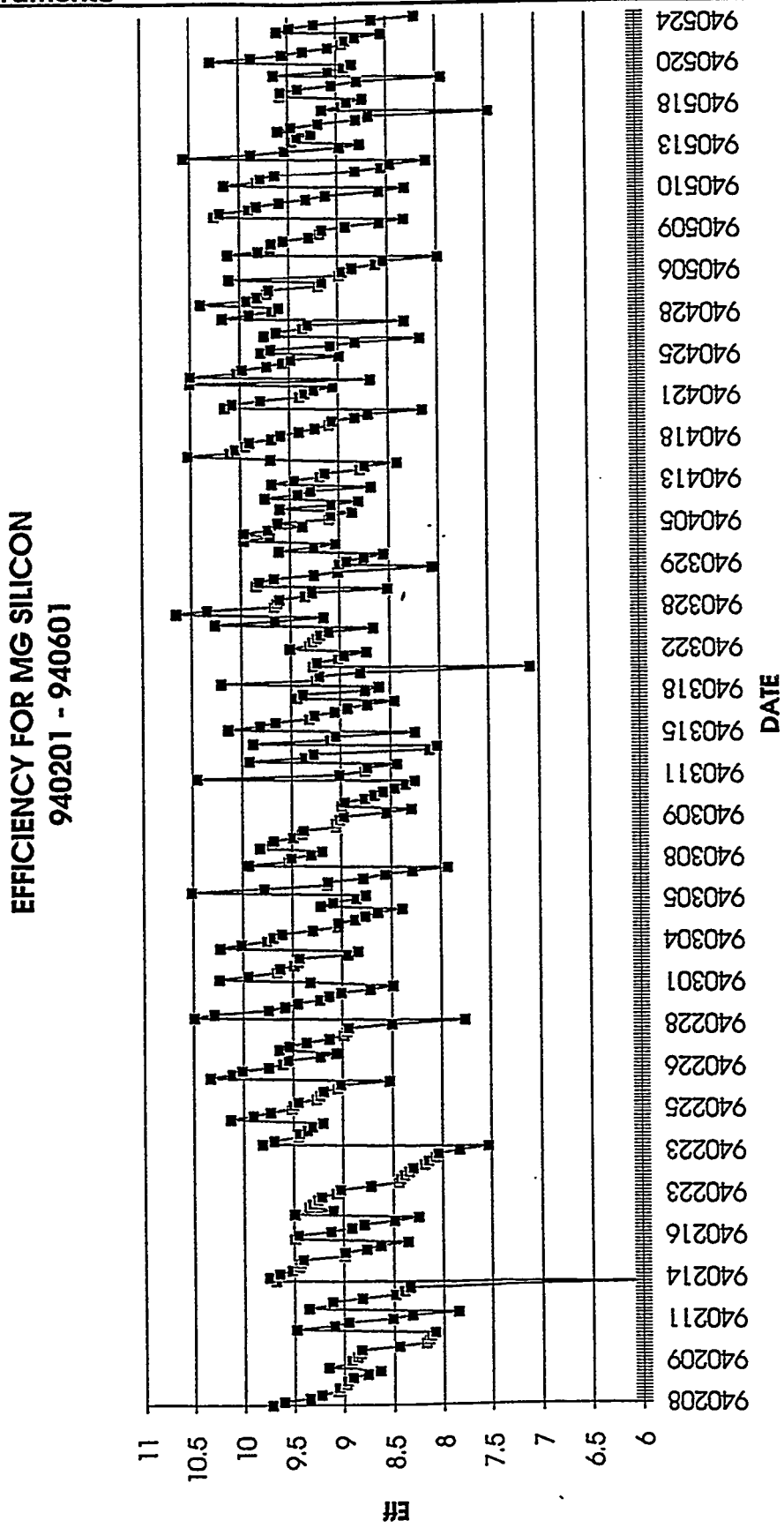

Figure 3. Efficiency of MG Silicon Cells

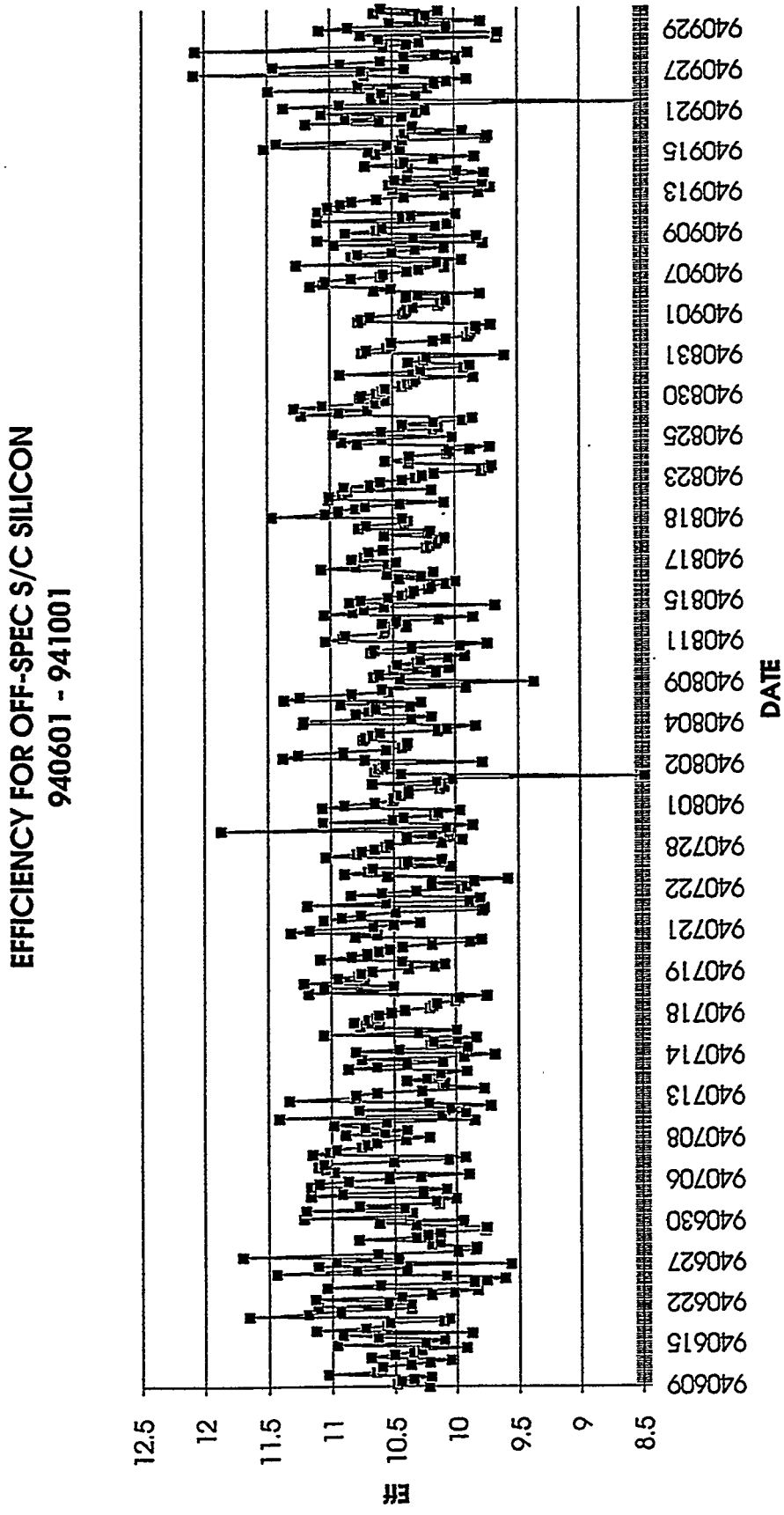

Figure 4. Efficiency of SG Silicon Cells

Future efforts will include implementation of a factory-scalable phosphorous doping process, and evaluation of the factory sphere etch prototype. Other work will include optimization of the denude, and segregation anneal processes for SG silicon.

TASKS 4 AND 5 INCREASE FABRICATED SPHERAL SOLAR™ CELL EFFICIENCY, YIELD AND RELIABILITY

Activities in Tasks 4 and 5 will be combined and addressed together in this section due to the close interaction they have with one another. Generally, if modifications are made to enhance either yield or efficiency, the other factor is enhanced as well. Therefore, their interaction makes it virtually impossible to address them separately.

The sphere material being used during the first half of 1994 was metallurgical grade (MG) silicon. As mentioned in Task 1, all process parameters were set and stabilized. Detailed electrical records were kept for both yield and efficiency. Statistical process control was initiated at all downstream processes as well. Foil spacing or tools being utilized were .027", .0285", .030", .032, and .035". Refer to Task 1 for the sphere ranges used in the above foil spacings. The goal for each of the tool sizes was to increase packing densities to the point that the spheres were as close as possible to one another but did not make contact. All foil was embossed and front bonded on the pilot line roll mill. Theoretical electrical values would be maximized at these conditions. Theoretical values also took into account perfectly round spheres. This however was not the case, so roundness ratios had to be considered for our sphere bin range selections.

From the data collected during this time period we saw that electrical yields and efficiencies were better in bin 1 lots than in bin 2 lots. The assumption was that our roundness ratios were not as good as we thought and that more sphere to sphere contact was being encountered in the bin 2 lots. This assumption was justified when comparing fill factors and open circuit voltage (Voc) between the bins. Voltage and fill factors in all cases were lower in bin 2 lots, indicating sphere damage. Table 4 below shows the performance factors tracked during the first 5 months of 1994. No values are available for June due to changeover from metallurgical grade (MG) silicon to semi-conductor grade (SG) silicon. Note that %Yield 32 indicates the Yield percentages of the .032" foil spacing. This tool was the best performing and was tracked as a check and balance of the overall process.

	Jan	Feb	Mar	Apr	May
% Yield all	86.7	79.3	77.6	81.2	88.6
% Yield 32	94.0	97.0	97.0	94.1	96.1
Avg Eff	7.8	7.9	7.7	7.8	7.4
Yield ≥8%	45.3	46.6	35.9	53.5	43.6

Table 4: Yield and Efficiency data for Jan 94 through May 94.

Several changes took place during this time that are worth noting. The .027" foil was clearly the worst performer from a yield standpoint, however the efficiency was lower overall in these tools. Notice the March figures in Table 4. A large percentage of the months output contained .027" foil, and all values fell. Based on the difficulties encountered with this foil size, this tool was removed from production at the end of March. The .030" tool was the second worst performer and tool analysis showed dimensions of the tool itself were mainly to blame. Please refer to Task 1 for more explanation of the tool analysis. Table 5 shows the % yield by tool for the first quarter of 1994.

Foil Spacing	% Yield
.027	48.3
.0285	75.7
.030	71.0
.032	96.0
.0335	84.0
Total	79.5

Table 5: First quarter yield data. Total population 3200 cells.

Other changes that were implemented in the beginning of 1994 which had significant impact include: 1) Polyimide chemistry was modified. This single change boosted overall yields from roughly 60% to 80%. 2) The gap width between cells on the front foil was reduced from .050" to .030" prior to 1994. The gap deformation was reduced which enhanced polyimide and via operations. Further reductions in gap width were pursued in the second half of 1994 which eventually led to a "no gap" strip design for the future factory proposals. 3) Sieving after the rollsorting operation was begun at the end of January to remove grossly oversize and undersize spheres and chips. This reduced sphere movement and improved yields. 4) All front bond parameters were optimized as detailed in Task 1. The front bond parameters can influence yield and efficiency greatly because too much pressure and temperature can enhance yield, but reduce efficiency. 5) Sphere size ranges were adjusted to compensate for out-of-

roundness in the spheres and movement inherent in the bonding process. Task 1 details the sphere ranges used for 1994.

Year end goals for both yield and efficiency were surpassed during the first six months of 1994. In May an overall yield of 89% and a new single cell record efficiency of 8.9% (before encapsulation) were achieved. A decision to change feedstock from metallurgical grade (MG) silicon to semiconductor grade (SG) silicon was made in May. New emphasis to modify processes toward future factory designs was also added as a goal for the second half of 1994. Both of these factors played heavily in the second half performance metrics.

As mentioned in Task 1, the second half of 1994 concentrated on moving from pilot line processes to factory simulated processes. The goal was to increase throughput and reduce cost in a factory environment. The major changes made during this time period included: the feedstock material changed from metallurgical grade (MG) silicon to semiconductor grade (SG) silicon; an automated front bond machine was incorporated into the front bond processes; punched front foil was phased in to replace embossed foil; a new front foil material supplier was brought on line; front foil thickness and hole size were changed; backbond process changed from static to roller; single front side thin (FST) etch process targets were incorporated; the gap spacing between cells was removed; the polyimide pre-bake was tested for elimination. Table 6 below shows performance data for the second half of 1994.

	July	August	September	October	November	December
%Yield all	69.9	67.7	83.8	75.6	37.4	27.5
%Yield 32	87.7	84.0	95.2	97.9	80.5	33.3
Avg. Eff.	8.8	8.7	8.9	8.9	8.2	N/A
Yield >9%	22.7	33.0	29.6	37.0	26.3	N/A

Table 6: Yield and efficiency data for July 94 through December 94.

Changing from MG to SG silicon material created many challenges. Resistivity levels were extremely high due to the new SG purity levels. Initially the yields were affected until the resistivity levels were stabilized. Testing was done with the existing baseline embossed front foil. The embossed database was very large and differences could easily be detected. Initial results of the SG material were very good. The higher purity silicon immediately showed efficiency improvements. The metric for tracking all cells above 8% efficiency (before encapsulation) was raised to 9% (before encapsulation) due to the improvements seen initially. The yields lagged slightly but recovered quickly to previous performance levels in September. Notice, however, that the efficiency improvement was realized immediately from the silicon feedstock change.

The automated front bond loader came on line in August and the remainder of the year all cells were produced on this equipment. Development of the bonding parameters and bonding package took place several months before the machine came on line. Pressures and temperatures varied significantly due to different system configurations on the automated equipment. We could not translate the settings on our pilot line directly over to the automated equipment, therefore several months of testing were required. Testing was started with embossed front foil again to utilize the database accumulated in the months prior. Both silicon feedstock and the automated front bond line yield figures stabilized in September.

The effect of punched front foil can be seen in the November and December yield figures above. Refer to Task 1 for an explanation of differences between embossed and punched foil. Clearly this modification had the biggest impact on our yields and efficiencies. Process adjustments have been made to help correct this problem. The new aluminum material supply started in the line in the middle of September and was used exclusively after that point. Initially we had problems with the spheres falling out and found that approximately 1,000 lb per side increase in front bond pressure on the pilot line roll mill reduced this problem.

The pilot line utilized static backbond to place the back foil on the cells. Static backbond utilizes an 80-ton press to push the backfoil against the silicon spheres with temperatures of 425 deg C. Several short duration push and hold cycles were needed to obtain a metallurgical bond. The resulting effect was a rather violent bumping cycle that was necessary to break through the oxide coating on both the aluminum and silicon. The cycle duration was 15 minutes for 3 strips.

Roller backbond, in contrast, utilizes a roll mill in place of the static press and only needs one pass through the roll mill to obtain a bond. The resulting strips had a more consistent bond from sphere to sphere, which was important when dealing with sphere size variation. The static bond tended to damage oversized spheres because they protruded above the surface of the other spheres and the press pressure was distributed over a smaller area. Roller backbonding utilizes smaller pressures distributed over a much smaller area. Pull tests showed that roller backbonding provided a more uniform bond across the cell surface and left larger aluminum dots on the tips of the spheres. A new single cell efficiency record of 10% before encapsulation was yielded on a test lot that was roller backbonded on .032" embossed front foil in late July.

The major thrust of the second half of 1994 was to move our processes toward those that would imitate actual factory processes. Unfortunately, our main goals of improving yields and efficiencies have suffered due to the numerous changes. This was anticipated, but we did not realize to what extent it would affect all the performance factors. As with major changes in the past, it will take time to understand and gain

control of these new process parameters. New measurement and statistical metrics have been put in place to track the affects of the new process changes.

TASK 6 INCREASE FABRICATED SPHERAL SOLAR™ CELL THROUGHPUT AND REDUCE LABOR COST

The focus of Task 6 in 1994 was on developing and integrating three pieces of prototype/initial factory scale equipment into the cell process pilot line. These pieces of equipment were procured and installed as risk reduction for future factory scale capital. This equipment included the Front bond workcell for loading and bonding the spheres into the aluminum foil, the Plaster rinse station for cleaning the foils of plaster residue created in the bonding process, and a Vision inspection system for accumulating parametric data on the cell processes.

Front bond workcell

This factory scalable robotic machine was developed by Automated Tooling Systems Inc. in Kitchner, Ontario, Canada. Its function is to load and bond spheres into a punched aluminum foil. The workcell was delivered to TI and installed on the pilot line in March. The next several months were dedicated to intensive process development with embossed front foils. Initially yields were quite poor, but after a couple of months the cells' quality, efficiencies, and yields were increased to the same levels experienced on the pilot line manual station. Process development then switched to punched foil and cell quality and yields declined once again. Currently efforts are underway to drive the process with punched foil up the improvement curve in the same manner as accomplished with embossed foil.

The demonstrated throughput for the automated system is 160 cells per hour with two operators. The machine can be broken down into six sections: 1. material input stations; 2. robotic arm; 3. vacuum chuck; 4. sphere dispenser / air knife; 5. vision system; 6. assembly stage; 7. clamshell; 8. roller press.

Plaster rinser

The Plaster rinse station was developed by Atotech USA, Inc. of State College, PA. It was delivered to TI in October and has now been installed on the pilot line. The filtration system initially designed into the system never performed to an acceptable level and caused substantial delays in the delivery. A redesigned filtration approach was developed and implemented to allow the system to be delivered. Final acceptance of the system based upon this new approach is now underway and should be completed in January. The station should be up and fully integrated into pilot line production shortly thereafter.

The demonstrated throughput for the rinse station is 1080 cells per hour with two operators. The machine can be broken down into five sections: 1. transport; 2. low pressure rinse with filtration; 3. high pressure rinse; 4. fresh water rinse; 5. dryer. Strips are transported through the machine by a two lane roller conveyor at the rate of 48 inches per minute.

Machine Vision Inspection System

A machine vision inspection system was developed by Texas Instruments in the first half of 1994 for measuring critical product parameters on front bond, VIA process and sphere roundness. This system is primarily used for statistical quality control and process development use. Data from this system assist process engineers in controlling process and further defining process control parameters. Throughput and accuracy of this system are significantly better than (>10X) current manual inspection methods.

TASK 7 SPHERAL SOLAR™ MODULE PRODUCIBILITY STUDY

During the first half of 1994, the module assembly area gained several semi-automated work stations to decrease material handling and tedious manual tasks, and to provide a more optimal level of automation.

First, a semi-automated weld station was completed. This station has an X-Y drive mechanism to index the ultrasonic weld head to each weld tab, and includes holding features for the aluminum bus and jumper ribbons. Also, a ribbon bending fixture premeasures the proper amount of aluminum ribbon needed for each module. Before this station was completed, the operators were required to slide a cumbersome aluminum weld tray beneath a fixed ultrasonic weld head, and ribbons were held by hand for welding.

Also completed was a contact weld station. This station ultrasonically welds the aluminum ribbons that exit the laminate to the copper clad aluminum ribbons for junction box connections.

Finally, a semi-automated steel rule die cell cutter was installed and is being used for production. This station uses pneumatic power to die cut the cells, versus the previous, difficult-to-use manual station. Additionally, this station has a vacuum hold down for the cells that makes die-to-cell alignment much easier.

During the second half of 1994 additional investigations were done to identify further tooling improvement which could be made in the module area. Also, several studies

were performed on the module design to determine where manufacturability could be improved.

A module assembly timing study (performed under Task 8) indicated that cell edge taping is one of the most time consuming process steps. This involves using tweezers to apply a three inch long, one-eighth inch wide piece of tape along the backfoil tab edge of the cell to reduce the opportunity for shorting. To see if "off the shelf" tape application equipment would perform the taping task, 3M Corporation loaned us an automated tape applicator. After some modifications to the tape feed mechanism, the applicator would reliably apply the tape to the edge of the cell, but the pinch roller system for feeding the cell through the machine frequently damaged the cells. Additional investigations show that equipment exists that would probably satisfy our tape application needs, but costs for a pilot line application would be over $25,000. These tape applicators are made by 3M Corporation and Tapeler Tape Machines, Inc.

Investigations were made into module frame design. Our current frame is joined at each corner with two screws. Optionally, the frame could be one continuous part (versus the existing four parts), using V-notches in the frame extrusion for three of the four corners and "wrapping" the frame aroung the laminate. Potential savings would be associated with the reduction in frame screws (two versus eight), and fewer parts to handle.

Changing the encapsulation materials used in module assembly is a subject of continued investigation, but no materials have been proven to replace the glass, EVA, and Tedlar-polyester-Tedlar (TPT) used to make standard modules. However, a study was undertaken to examine the packing factor, or the percent of cell area compared to the entire area of the module, measured to the outside edges of the frame. An increase in packing factor would mean a decrease in cost per watt of our product.

To quantify our current packing factor, cell sizes were compared to the frame size. The packing factor ranged from 79.7% to 81.9%. Next, calculations were made that allowed for a uniform .06 inch gap between the cells and .25 inch border from the edge of the outside cells and ribbons to the edge of the laminate. The results (based on theoretical largest cell):

New packing factor:	88%
Glass / EVA / TPT area reduction:	7%
Frame length reduction:	3%
Frame width reduction:	4%

These area and length reductions would translate directly into savings on lamination and framing materials. These changes have not been implemented on our pilot line because changing the materials and tooling would be much more expensive than any savings derived from using less module assembly materials, since our existing production rates are quite low.

TASK 8 SPHERAL SOLAR™ MODULE PRODUCTION LINE FLOWS AND INCREASED AUTOMATION

Prior to the beginning of 1994, TI contracted with an automation supplier to propose an automation plan for module assembly. They generated a complete factory equipment layout and written descriptions for each of the module assembly process steps. Additionally, the supplier provided cost estimates for the entire system. Specific equipment was selected for various areas, such as lamination, cell testing, module testing, ultrasonic welding, and glass washing. Limited prototyping and testing on cell handling, cell carriers, and lasermarking was performed.

Beginning in 1994, TI contracted with another automation supplier to begin factory planning and prototype work. This supplier generated a first-pass process flow chart and proposal for a weld tab bending prototype.

As a result of the work with both suppliers, we have determined that there were no "high risk" areas that needed continued investigation.

The plans generated by both suppliers follow the current optimized process flow that is in use on the pilot line. (However, there are a few exceptions to this process flow needed to enhance the effectiveness of the automated material handling.)

The second half of 1994 focused on quantifying the time required to make a module, from receiving the strips in module assembly to inserting the completed module in a box. A formal time study was performed to provide the required data. This time study evaluated each process step. This study did not account for any cell yield loss, which is identified at cell test, and was based on a 40 cell module.

Process step	*Minutes/module*	*Process step*	*Minutes/module*
1. Cell separate	40.22	11. Laminate	29.0
2. Die cut	28.28	12. Trim laminate	1.85
3. Weld tab cut	6.67	13. Contact weld	7.0
4. Cell test	47.17	14. Tape laminate	5.2
5. Tape cells	75.83	15. Frame	4.84
6. Load tray	33.42	16. Junction Box	2.94
7. Weld cells	12.0	17. Hipot test	5.0
8. Fold ribbons	10.63	18. Final IV test	3.23
9. Glass wash	3.5	19. Box	12.0
10.Layup	23.12		

Total: 351.9 minutes per module, or 5.87 hours per module. For all steps except for portions of the Layup step, only one person is performing the task. Also, the Tape Cells process step can be performed by several people (it is not equipment limited),

thereby enabling this step to take less than one hour for forty cells. The equipment limited process step is Cell Test at just over 47 minutes per module.

These data demonstrate that with a work force of at least seven operators, module throughput (on an average 8-hour shift) could be at least one module per hour.

TASK 9 ASSEMBLED SPHERAL SOLAR™ MODULE EFFICIENCY

Outstanding success can be reported towards the milestones for Task 9 in 1994. A module aperture efficiency of 10.3% has already been verified by NREL. This efficiency exceeds our Phase III (third year) milestone of 9.7%. Major activities that will be discussed in this section include investigation of new encapsulation for obtaining optical boosts, reliability testing of new materials, and reduction in non-active module area. A summary of the efficiency results follows.

The Spheral Solar™ cell has an active surface area of 75 to 80%. The rest of the surface is aluminum. In the standard glass lamination normal light striking the aluminum will be reflected away from the device and be lost. Several designs for optically focusing the light away from the aluminum and onto the spheres were developed. Most of the designs required replacing the glass superstrate with a polymer. Some of the designs also require replacing the EVA encapsulation. The designs, and the status of each, will be discussed below.

Spray-on Encapsulation

In the late 1980's it was discovered that by spraying a clear acrylic coating onto the Spheral Solar™ cell, optical boosts in efficiency of 15 to 20% could be achieved (see Fig. 1). The integrity of this film was always a big concern. Earlier this year a search for a more robust coating was completed. The two most promising candidates are a fluoropolymer coating and a polyurethane/acrylic clear coat used in the automotive industry. The automotive clear coat has endured 111 days of outdoor exposure with no degradation. Both of these candidates show improvements in ability to repel dust, but neither candidate passed the IEEE cut test. Adherence of the solar cells to the substrate was also a problem with the spray-on module package, which caused failure during temperature cycling environmental tests. The work on spray-on encapsulation is now on hold pending the outcome of more promising optical encapsulations.

Air Gap Optics

The Air Gap Optics design uses the same concept as the spray-on optics. Normal incident light is bent a polymer air interface so that it is reflected into the sphere (see fig 5).

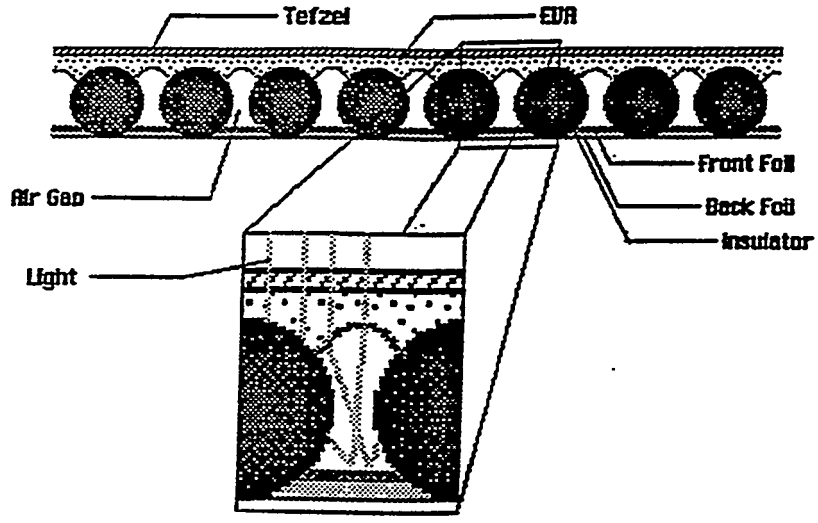

Figure 5. Air gap optics

The advantage of this design is the top surface is flat eliminating the dust collection problem. Optical efficiency boosts range from 12 to 16%. The biggest concern with this design is the reliability issues surrounding intentionally leaving an air gap in the encapsulation. Different materials have been prototyped with varying degrees of success. Temperature cycling from -40 deg C to 90 deg C fifty times, cycling from -40 deg C to 85 deg C at 85% humidity ten times, and performing the IEEE cut tests (dragging broken hacksaw blade) were used for screening material candidates. One cell to full size modules were used in the experiments. Table 7 below summarizes the results of the three IEEE environmental test standards used as a screen for potential materials.

Superstrate	Encapsulant	T50	10HF	Cut Test
Oriented Acrylic film	Acrylic adhesive	fail	fail	pass
Oriented Acrylic film	Pressure sensitive adhesive	fail	fail	pass
Unoriented Acrylic film	Acrylic adhesive	pass	fail	pass
TEFZEL	Thin EVA	NA	NA	fail

Table 7: IEEE Environmental Test Results

The acrylic films all had problems with thermal expansion/shrinkage at the high temperatures, 90 deg C and 85 deg C, in the T50 and 10HF tests. Higher Tg acrylic copolymers are currently being investigated to solve this problem. Work is currently

being conducted to see if the TEFZEL/Thin EVA package will pass the environmental tests. Efforts to reinforce the TEFZEL so that the cut test could be passed are also being investigated. It should be noted that TEFZEL with standard EVA thickness' (18 mils) does pass the cut test, but does not maintain the air gap.

SMRC

The Spheral Mini Reflector/Refractor Concentrator (SMRC) advances the concepts discussed above. By using reflective or refractive microstructures, light can be manipulated in such a way as to reduce the number of spheres per unit area required for the same or more power output. Much of the work done here has been modeling. Two prototypes have been built. The two basic concepts on which there are an infinite number of variations, and the work done so far in developing working prototypes will be discussed below.

The refractive concept (SMRC 1) illustrated in Figure 6 uses a structured superstrate to focus light on the spheres and away from the aluminum. Extensive modeling was done at Sandia National Labs with the help of Dr. Alex Maish. An existing concentrator lens design software package (developed by Larry James of James Associates) was modified for the TI cells. The ray trace data for the optimum design shows a ~70% reduction in silicon spheres with an 18-35% boost in cell efficiency. The benefits are enormous.

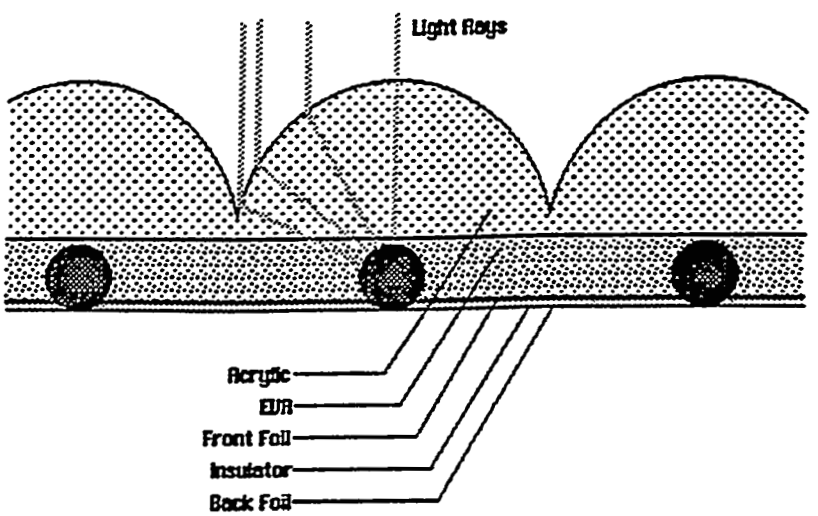

Fig. 6 SMRC 1 Concept

The design concerns for SMRC 1 are dirt collection on the textured superstrate, superstrate material, and the ability to align microstructured cover with the sphere pattern. Also, this design requires tracking the sun. To test the concept a special aluminum foil punch was fabricated and aluminum foils were prepared with the wider spacing. A mold with the design pattern developed with the Sandia model was machined and lens films were made from acrylic. Prototype cells were made and

laminated to the acrylic lens. Several problems arose. The cells, being the first ones with the new tooling, had irregular spacing and crumpled aluminum which made alignment with the lens sub-optimum. Also, the acrylic lens warped during curing, further degrading alignment. With these problems, efficiency was only half of the predicted performance. It is felt that this can be improved.

Inactive area in the standard glass power module was another area targeted for improvement. Currently, the glass modules produced on the pilot line have a packing factor of 81%. By reducing the gap between cells and around the border, and by folding cell string leads under the cells, the packing factor can be increased to 90%. Reliability tests are underway for folding leads under the cells. All other changes will not be made until factory scale up.

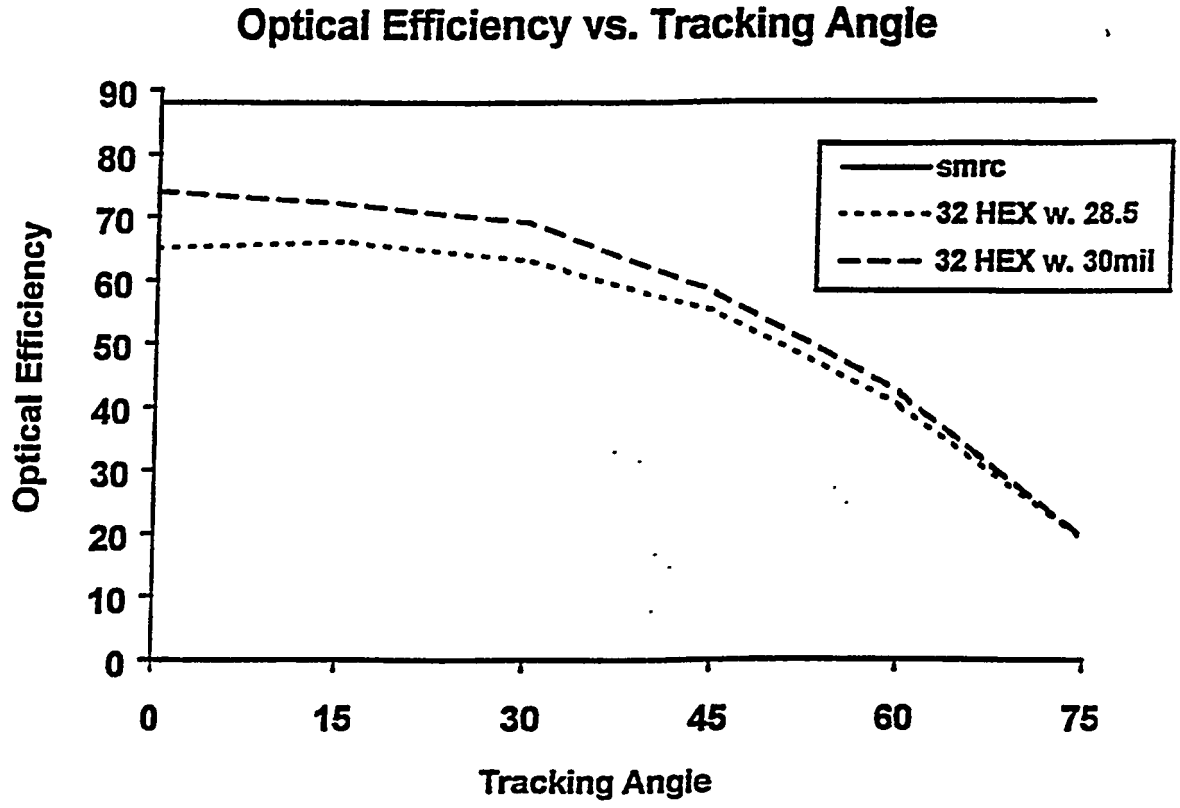

Figure 7. Model Output vs. Tracking Angle

The module efficiency improvement that have occurred in 1994 can be attributed to sphere and cell quality improvements, and the change to off-spec electronic grade silicon. The work continues in the module area to add to these improvements through optics and the use of new materials. All theoretical calculations indicate another 15 to 20% improvement in efficiency is possible through optical enhancement alone.

TASK 10 SPHERAL SOLAR™ MODULES UTILITY SPECIFICATIONS:QUALITY FUNCTION DEPLOYMENT STUDY

The activity for Task 10 has concentrated on information gathering during 1994. Utility personnel were interviewed at the Soltech94 and UPVG94 meetings to obtain their inputs on both the modules and balance of system hardware they expect to need. We have obtained the Pacific Gas and Electric Power Producer's Interconnection Handbook, which is probably the most complete of its kind. TI had done an earlier Quality Function Deployment Study on modules (but not specifically utility modules); the results have been reviewed and found to contain a number of still relevant inputs that will be incorporated into the present work.

The most significant findings to date have been as follows. To think of utility photovoltaics was at first expected to mean large installations of 100's of kW installed in a sub-station-like area that was "behind the (utility) fence". However, this is not an accurate picture. Utilities have become involved in the full range of photovoltaic applications, from 20 W SCADA systems to 100 W water pumping systems, to residential roof mounted systems of a few kW's, to commercial/industrial roof mounted systems of a few 10's of kW's, in addition to the expected large systems. Therefore, the utilities will require a range of module and balance of system products to be fully satisfied.

One problem that has been identified in this work is the lack of a good set of standards to refer to for qualification tests, and a lack of agreement between existing documents. The most relevant document should be the IEEE Standard 1262, but it continues to remain in draft status. The SERI (NREL) Interim Qualification Test document is good but not official. The JPL Block V, from which much of what has been done since was derived, is very old and is sometimes in conflict with the IQT. In addition, the IQT and 1262 draft differ from the equivalent Europeon IEC 1215 in the degradation allowed after life test. The US documents allow 10 % degradation while the IEC 1215 (and JPL Block V) allow only 5 %. In addition, the UL 1741 document for inverters is also in draft status. These issues are problems because one comment that was made repeatedly by utilities is that photovoltaic systems must pass these tests to be acceptable.

A first draft of the Handbook has been written.

CONCLUSION

1994 was an extremely productive and successful year for the Spheral Solar™ technology. All of the PVMaT milestones were met or, in many cases, exceeded. Great strides have been made in virtually every process area toward the overall PVMaT program goal of advancing the technology by reducing production costs, increasing module performance, and expanding commercial production capacities through analysis of the performance of the pilot line.

Changes were made to the materials being used, and processes were developed and modified as necessary for preparation of scaling up to megawatt levels of production. Fundamental changes, such as converting to higher purity silicon and the introduction of the fused powder process, have enhanced the technology potential tremendously. Continued process development and pilot experience continues to build confidence in the technology.

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1995	Final Subcontract Report , 24 January 1994 - 23 January 1995

4. TITLE AND SUBTITLE

Photovoltaic Manufacturing Technology Phase 2B: Spheral Solar™ Technology

5. FUNDING NUMBERS

C: ZAI-4-11294-04

TA: PV550101

6. AUTHOR(S)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

TP-411-20018

DE95013144

11. SUPPLEMENTARY NOTES

NREL Technical Monitor: R. Mitchell

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

UC-1280

13. ABSTRACT *(Maximum 200 words)*

This report describes work performed by Texas Instruments Incorporated (TI) to improve Spheral Solar™ technology product quality and to accelerate the scale-up of production, resulting in substantial reductions in manufacturing costs. The Spheral Solar™ manufacturing sequence is divided into three major process areas: sphere fabrication, cell building, and module assembly. The objective was to conduct parallel activities to address significant portions of the Spheral Solar™ PV cell and module manufacturing process. Included were tasks to (1) increase the efficiency of the spheres, cells, and modules; (2) increase the yield and throughput of spheres and cells; (3) increase the fabricated cell reliability; and (4) reduce cell and module labor costs. Studies were also performed on module producibility, module production line flows, increased automation, and required module specifications. TI made excellent progress in continued process development on the current pilot line. Critical, higher risk pieces of production-scale equipment were added to the line for early problem identification, redesign, and process modification. Other sub-processes had production scale equipment concepts developed and prototyped.

14. SUBJECT TERMS

manufacturing ; Spheral Solar™ ; photovoltaics ; solar cells

15. NUMBER OF PAGES

37

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL